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Prediction model for fatigue life considering microstructures of steel

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Abstract

In fatigue life, crack initiation and crack propagation is considered separately. Behavior of large crack propagation is explained on the Paris equation. However, there is no model to simulate the behavior from the crack initiation to the large crack propagation. One of this cause is that fatigue life can varies greatly thanks to material microstructures and manufacturing and change of stress. Especially to think the effect of material microstructures is important in materials development. However, there is no model considering quantitative effect of material microstructures.

We made prediction model for fatigue life considering material microstructure. This model is for the ferrite-pearlite, most popular steel for the structure. Using FEM analysis, this model gets stress on the specimen and divides surface of the test piece into small squares, and fills the squares with grains using Monte Carlo method based on distribution of the grain size. The model gives each grains crystal orientation randomly. In each squares, from the stress and the crystal orientation, this model judges the initiation of the crack on grain. This model simulates the propagation of small crack from the crack nucleation. From the stress and the crystal orientation and the interaction between the slip band and the grain boundary, this model simulates the propagation of the small crack thinking the interaction with grain boundaries.

To estimate exact fatigue life, this model needs the parameter of the small crack propagation. This parameter is inherent to each material. We conducted some fatigue experiments and observed the propagation of the crack in detail. We conducted fatigue experiments with another distribution of grain size to validate our model and we got good agreement with the experiments and the model.

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Keywords: fatigue; microstrucutere; ferrite-pearlite;

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1. Introduction

Since microstructure mainly affects the fatigue life in the initiation of high-cycle fatigue, various studies using microstructure were conducted such as Li et al (2010), Hutchinson et al (1992) and Coulombier et al (2010). There are many attempts to model the crack front considering the affection of micro structure. Penau et al (1976) has shown that micro structure affects the progress of the fatigue damage and changes the initiation of crack and early propagation of crack by the approach that relates microstructure and behavior of micro flaw. McDwell (1976) has shown that micro structure can affect the initiation and propagation of small crack in high-cycle fatigue. They are fundamental approaches to the change from small crack to crack in fracture mechanics.

Miller (2000) argued the relationship between micro structure and small crack. There are modelling based on the dislocation theory and modelling considering the crack initiation on slip bands such as Bayley et al (2006) Kuroda et al (2008) and Evans et al (1981). Modelling based on the dislocation theories are aimed for the elucidation of phenomenon and it is difficult to predict fatigue life in radical use. In the modelling considering the slip band, Tanaka et al (1981) have proposed modelling of small fatigue crack growth interacting with grain boundary. Based on this theory, many studies are conducted such as Tanaka et al (1986) and Akiniwa et al (1998, 2000). Hoshi et al (1987) modeled the initiation of crack using relationship between slip band and propagation of crack. But, this is the conceptual model of the slip band and crack. Thus this is not for prediction of fatigue life and can't be used in real materials. Kirane and Ghosh (2007) tried to use non-local slip model on real 3D microstructure, but cannot relate 3D microstructure and applied stress because they are complex. The model of Tanaka et al is epochal in understanding the phenomenon but there are some problems in practical use. This study aimed for the fatigue life prediction model considering the micro structure by expanding the existing theory.

Nomenclature

a	length of crack
c	length of slip band
l_n	distance from crack nucleation to (nth) grain boundary
σ	applied stress
σ_n^{f}	friction stress of (nth) grain
G	shear modulus
ν	Poisson's ration
δ	crack tip opening displacement
ν	the microscopic stress intensity factor
$\bar{d}$	averaged grain size

2. Fatigue test for the detail observation

In this experiment, tested steel A, B and C were used. These steel's chemical composition is shown in Table.1. Ferrite grain size and pearlite-band were measured in each tested steel. In measuring, ferrite grains were regarded as circles. EBSD was used to measure ferrite grain size. The width of pearlite-band was measured. Fig. 1 shows Cumulative probability distribution of ferrite and pearlite grain size. From this result, ferrite grain diameter of test steel A is smallest, that of test steel C is largest, and width of pearlite-band of test B is larger than the others.

The form of specimen in this experiment is shown in Fig. 2. This specimen has notch in the center. By this notch, stress concentrates on the center of the specimen and crack initiation can be seen mainly in the center. This is for the aim to reduce the area to observe for cracks.

Fatigue test was conducted for the detailed observation of crack using tested steel B. In this experiment, sine-wave load was used and the frequency was 20Hz and stress ratio was -1. Before the experiment, we got strain by using strain gage and compared with strain calculated from FEM and we confirmed there is no machine eccentricity. The surface of specimen's notch is observed by optical microscope. The observation was conducted when loaded 2000^{n} times. After the crack length got enough long, the observation was done on specific time. The point of crack initiation was sought. We did etching on the notch of this specimen by 2% nital. Nital corrodes pearlite and I can distinguish pearlite from ferrite. Photograph of specimen loaded few times and that loaded much time are compered to find the crack initiation point and the point of crack initiation is marked in Fig. 3(a). Watching crack initiation point on the photograph of crack with nital, the grain where crack initiates can be identified, thus crack initiation occurs in ferrite.

Table 1. Chemical compositions of tested steel

Steel	C	Si	Mn	P	S	Al	N
A	0.07	-	1.5	0.01	0.003	0.03	0.002
B	0.18	0.15	0.99	<0.002	0.0005	0.019	0.0008
C	0.087	0.15	1	<0.002	0.0005	0.018	0.0009

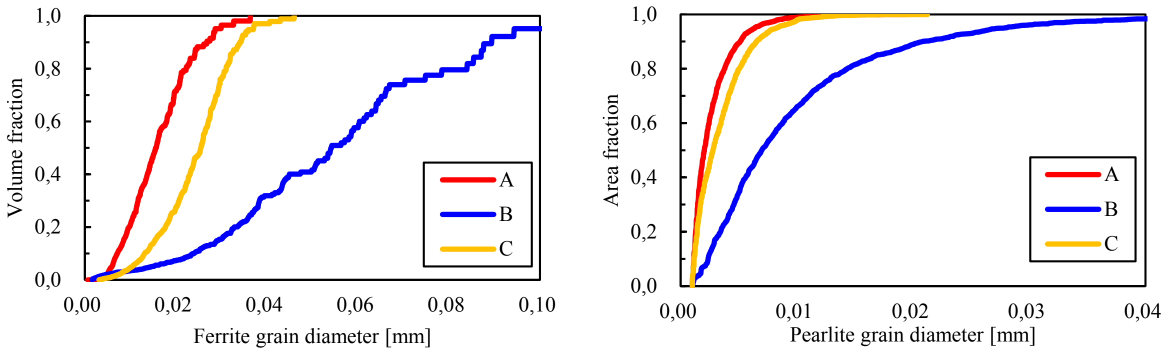

Fig. 1. Cumulative probability distribution of ferrite and pearlite grain size

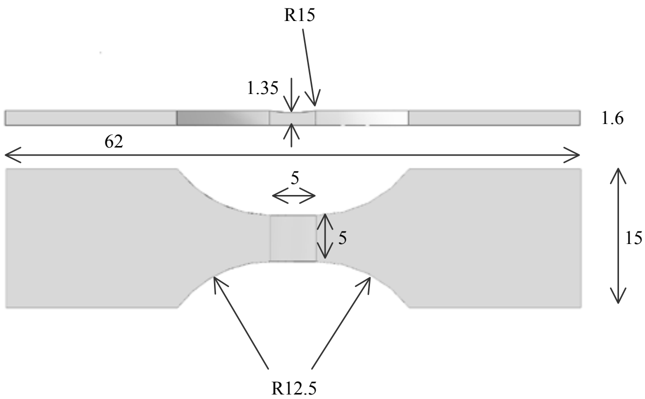

Fig. 2. Configuration of fatigue specimen

3. Model development

From the detail observation of crack, the crack initiation occurs on ferrite grains on the surface of specimen. The crack propagates into the inner specimen. In this study, the surface of the specimen and the inner specimen were modeled separately. This study models the specimen by 2D of surface and 2D of inner specimen.

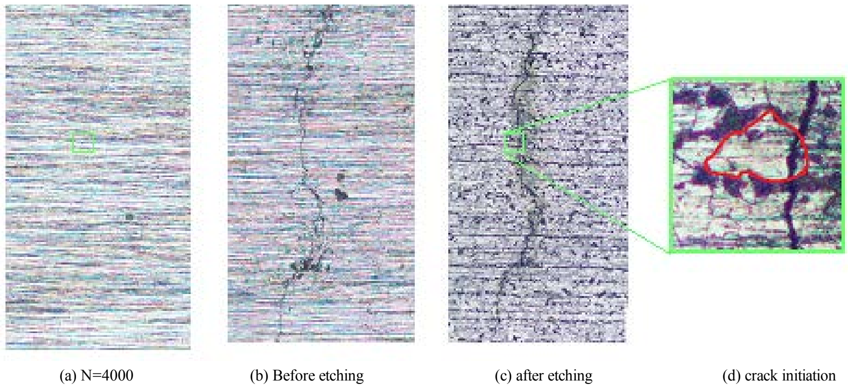

Fig. 3. Photograph of crack initiation

3.1. Surface model

Ferrite pearlite steel consists of layered structure and each layer is made of grain. Modelling of ferrite-pearlite steel was based on model of Nemoto et al (2016), ferrite grains and pearlite particles are regarded as spheres and spheroids, respectively. From the observation, minor axis of pearlite is same as pearlite-band and major axis of that is as long as diameter of ferrite. These grains consist of the layered structure. Based on this modelling, ferrite grain is regarded as a circle and pearlite grain is regarded as an ellipse in this study.

This is about modelling for the surface where cracks initiate. Surface of specimen is divided into square area elements and grains of ferrite and pearlite are filled in these area elements. These area elements are enough large to fill the biggest grain. The area rates of ferrite and pearlite are calculated and grains are filled into area element based on Monte Carlo method. First which grain is filled is decided according to ferrite area rate. Second the size of grain is decided according to the distribution of grain size. When grains are filled, random crystal orientations are added. This process is repeated till the sum of the area of filled grains is larger than the area element.

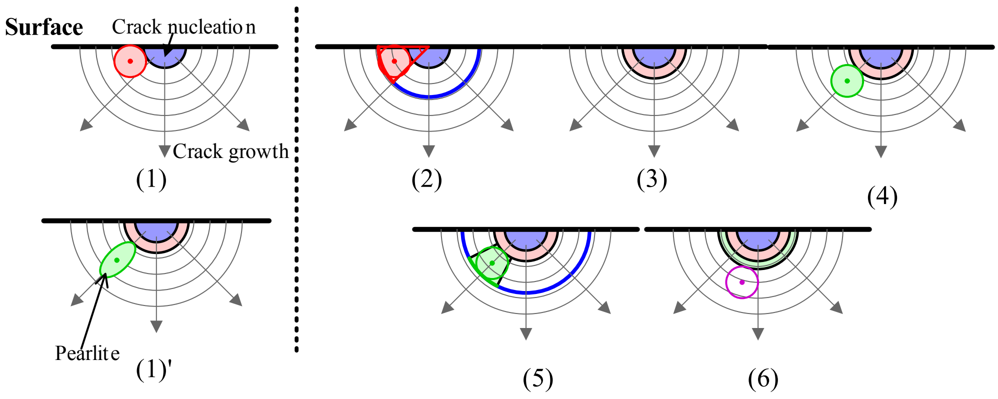

Fig. 4. Schematic diagram of grain arrangement

3.2. Inner specimen model

This is about modelling for the inner specimen where cracks propagate. In the modelling of inner specimen, ferrite grain is regarded as a circle and pearlite grain is regarded as an ellipse in the same way as surface model. To utilize two-dimensional modelling of small fatigue crack growth interacting with grain boundary, complex arrangement of grains is simplified. The arrangement of grains on the plate where cracks propagate is averaged into semi-circular lows of grains. The way to simplify the arrangement of grains is described below.

1 First grain is placed next to the crack nucleation (Fig. 4 (1)).
2 Placed grain is transformed into a part of sector same as the grain in size (Fig. 4 (2)).
3 Central angle of that sector is calculated (Fig. 4 (2)).
4 The grain is transformed into a semicircle same in size (Fig. 4 (3)).
5 Next grain is placed next to the semicircle (Fig. 4 (4)).
6 Every time total of central angle is more than π, these sectors are transformed into averaged low of grain.

The Schematic diagram of these processes is shown in Fig. 4. Placing pearlite grain, the grain is placed as the major axis is for crack propagation direction (Fig. 4 (1)').

Then, this study uses modelling of small fatigue crack growth interacting with grain boundary. In 3.2, this thesis is explained. When crack tip is in the (jth) grain and slip band tip is in the (nth) grain, there is the relationship between crack length a and slip band length c.

$$\frac{\pi}{2}\sigma - \sigma_j^f\, cos^{-1}\left(\frac{a}{c}\right) - \sum_{k=j+1}^{n}\left(\sigma_k^{\mathrm{f}} - \sigma_{k-1}^{\mathrm{f}}\right) cos^{-1}\left(\frac{l_{k-1}}{c}\right) = 0 \tag{1}$$

δ is represented as

$$\delta = \frac{1}{\pi^2 A}\left[2\sigma_j^f \ln\left(\frac{c}{a}\right) + \sum_{k=j+1}^{n}\left(\sigma_k^f - \sigma_{k-1}^f\right) g(a, c, l_{k-1})\right] \tag{2}$$

$$g(x, c, a) = a \ln\left|\frac{(c^2 - a^2)^{\frac{1}{2}} + (c^2 - x^2)^{\frac{1}{2}}}{(c^2 - a^2)^{\frac{1}{2}} - (c^2 - x^2)^{\frac{1}{2}}}\right| - x \ln\left|\frac{x(c^2 - a^2)^{\frac{1}{2}} + a(c^2 - x^2)^{\frac{1}{2}}}{x(c^2 - a^2)^{\frac{1}{2}} - a(c^2 - x^2)^{\frac{1}{2}}}\right| \tag{3}$$

Fatigue life can be calculated by following formula called Paris equation.

$$\frac{da}{dN} = C\,\delta^n \tag{4}$$

C and n are material property. In this model, using sufficiently small a, N is represented as

$$N = \sum \frac{da}{C\,\delta^n} \tag{5}$$

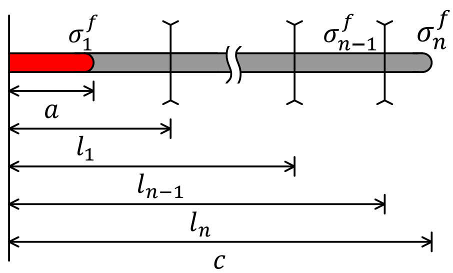

Fig. 5. Crack tip slip band model

3.3. Flow of model calculation

Place where the crack can initiate is defined as active zone. Active zone is divided into area elements. Ferrite and pearlite grains are filled by Monte Carlo method based on distribution of the grain size. The stress tensor of active zone is obtained by FEM analysis. Crack initiation is judged from the stress tensor and crystal orientation. If crack initiates, this model considers crack propagation. Fatigue life is calculated. To the all grains, these process of 1~7 were done and the smallest fatigue life is defined as the fatigue life. The flaw of calculation is described in Fig. 6.

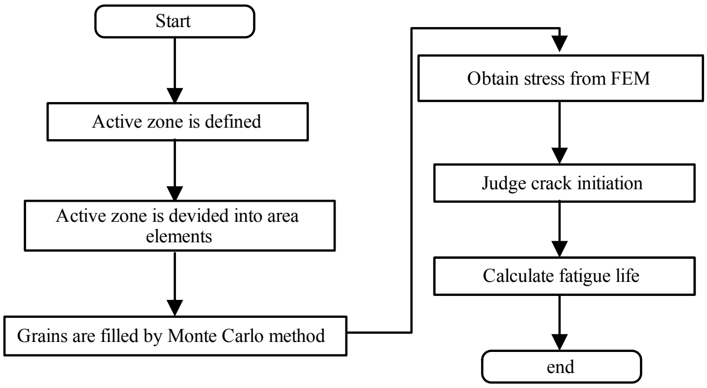

Fig. 6. Flow of model calculation

4. Validation of the model

4.1. Model preparation

Active zone where the crack initiation was observed in the fatigue test is defined as 3mm × 5mm center of the specimen. Considering the size of ferrite and pearlite grain, area elements were defined as the square 0.1mm on a side. There are 1500 area elements on the surface. Abaqus6.14 was used in FEN analysis.

Friction stress is identified by each grain. Friction stress can vary by grain size. The relationship between grain size and yield stress is represented by following formula (6) called Hall-Pecth relation.

$$\sigma_{\mathrm{Y}} = \sigma_0 + \frac{k}{\sqrt{d}} \tag{6}$$

k is generally said to be 21 such as Chokshi (1989). From the formula of Ohata et al (2013), the relationship between the friction stress of ferrite and that of pearlite can be described as

$$\frac{\sigma_{\mathrm{Y}}^{\mathrm{F}}}{\sigma_{\mathrm{Y}}^{\mathrm{P}}} = \frac{198}{276} \tag{7}$$

$$\sigma_{\mathrm{Y}} = \left(1 - S_{\mathrm{f}}^{\mathrm{P}}\right)\sigma_{\mathrm{Y}}^{\mathrm{F}} + S_{\mathrm{f}}^{\mathrm{P}}\,\sigma_{\mathrm{Y}}^{\mathrm{P}} \tag{8}$$

where, σ_Y^F is friction stress of ferrite, σ_Y^P is friction stress of pearlite, S_f^F is ratio of ferrite area and S_f^P is ratio of pearlite area. From these formulas, the friction stress of test steel B and C were calculated. The result of friction stress is described in Table 2. These friction stresses are divined by 2 since this model uses friction stress in direction to shearing.

Table 2. Respective values of steel B and C

Steel	Mean area diameter of ferrite [mm]	Area fraction of pearlite S	Yield stress σ [MPa]	σ_0 [MPa]	σ_Y^F [MPa]	σ_Y^P [MPa]
B	0.0596	0.27	216	130.0	117.5	163.8
C	0.0244	0.13	260	125.6	119.4	166.6

4.2. Model validation

Fatigue test for the S-N curve was conducted using tested steel A, B and C. The experimental condition is same as that of fatigue test for detail observation. If the specimen is unbroken loaded more than 10^7 times, this stress is less than the fatigue limit and I stopped the experiment before the breakdown. From the result, we can see that the smaller the grain is, the longer the fatigue is and this corresponds with the preceding study of Anderson (2005). Test steel A and C are almost same in the size of pearlite-band, but different in the size of ferrite. The result of the experiment shows that the difference of the ferrite can affect the fatigue life. Calculations on the test steel B were done several times changing the parameter of formula (5). By changing parameter n, the inclination of S-N curve changes and by changing parameter C, intercept of S-N curve changes. Compering the result of experiment, parameter C and n are decided. As a result, c=2.75, N=1140 were chosen. Calculations on the test steel A and C were done using the parameter which is decided by calculation of test stress A. this result is shown in Fig. 7. From the result, it can be said that this model can predict fatigue life in both test steel A and C

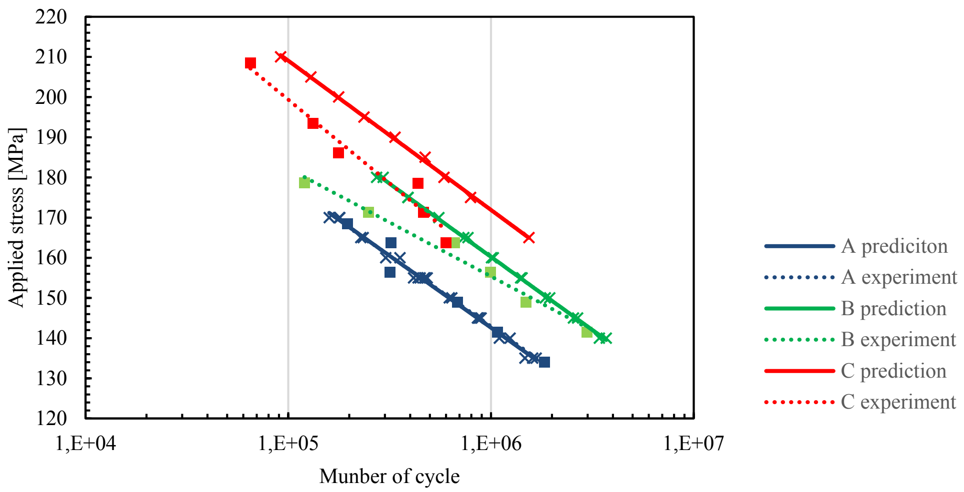

Fig. 7. Comparison of experiment and predicted result

Conclusions

We created fatigue life prediction model for ferrite-pearlite expanding modelling of small fatigue crack growth interacting with grain boundary. That crack initiates in ferrite grains is confirmed from the detail observation. The surface of the specimen and the inner specimen are modeled separately. Ferrite grain is regarded as a circle and pearlite grain is regarded as an ellipse. This study uses two-dimensional modelling of small fatigue crack growth interacting with grain boundary by making the averaged grain lows. The fatigue test was conducted using three types of steel for S-N curves. The friction stress of ferrite and pearlite were calculated from formula of Hall-Petch. The parameter of crack propagation was identified by calculating for the one steel. Calculating on the other two steels using the same parameter, we obtained good agreement of model prediction with experiment.

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